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CASEBOOK

OF

BIBHAS DE

JAM TOMORROW!

(Promise of plasma fusion energy)

When a public-funded, Manhattan Project-like
crash program goes nowhere in decades,
is it not time to dredge up some physics issues
this establishment deep-sixed?
My issue has it that processes in
a plasma can drain the energy
in the confining magnetic field.
The concerning new consideration was nixed
repeatedly – twenty-five years ago.

INTRODUCTION

We want to discuss magnetic confinement of fusion plasma. The confining static magnetic field is provided by an external "battery". Given the internal resistance of the battery and the resistance of the magnetic coil, the steady-state electric current I_0 and the steady-state magnetic field B_0 are established. The plasma is not seen in any way as a "load" on this battery.

But if somehow this magnetic field energy is continuously dissipated by processes in the plasma, the battery would continuously reestablish the current I_0. Thus, unless an experimenter is properly monitoring the state of the battery, he would never know if there is a load in the plasma. There exists no evidence either way.

The current theory of fusion forbids any such dissipation. The field B_0 is inviolate, depending only on the source. The following theory says it can decay due to processes in the plasma.

But let us step back for a moment from the plasma and address the fundamental issue in a different arena. This issue: Can the energy in a magnetic field at a location far away from the source be locally used (drawn down) by local processes? The answer in today's fusion science is NO. Nothing can be done to this field without accessing its source. *This position is in fact ancient and superseded.*

Consider a point in Jupiter's magnetosphere. A compass needle placed there aligns itself to the planet's magnetic field whose source is inside the planet. Now suppose this source vanishes instantaneously. What will happen to the compass needle. Nothing will happen for a while. Thus, to this extent, there is a physics disconnect between the source and a far location. Things can happen in that location without the source participating. *This is the correct physics*.

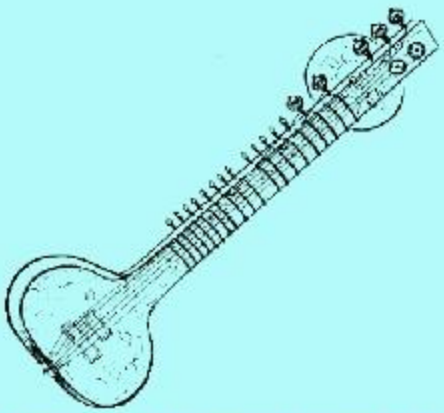
Before going to the case of plasma that is somewhat complicated, I have addressed this drawdown happening in a dielectric fluid. I then tried to transfer this result to plasma. There I encountered a stone wall. In spite of many attempts, the idea could not be published.

05/13/2021

PEDAGOGY: MAGNETOSTATIC ENERGY DRAWDOWN

The following material is from my webpage:
www.bibhasde.com/drawdown.html
that I put up many years ago to explain this basic phenomenon at a gut level.

BIBHAS DE EXPLAINS MAGNETOSTATIC ENERGY DRAWDOWN

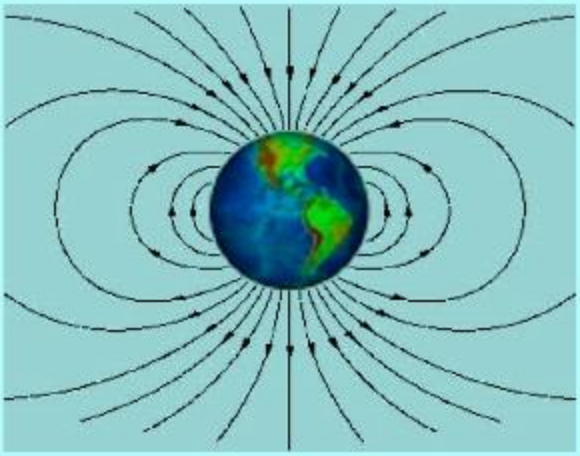


The strings of a sitar are under tension and thus have stored mechanical energy. When one plays a sitar, he produces sound energy. This latter energy comes from the act of plucking/striking the strings, and not from the stored energy of the strings. The stored energy is not available. The player in effect adds to this stored energy and then takes out what he adds in the form of sound.

However, if a string snaps at some point during plucking/striking, then the entire stored energy of the string is released at that point. The release appears as the kinetic energy of the snapping ends of the string. The stored energy is drawn down.

Strings of the Sitar

Planetary magnetic field, at some point far away from the planet, has energy stored locally. But an electron moving in this field cannot in any way make use of this energy – it is not available.



However, a spiraling electron under the influence of external forces can exchange energy with this field (add, subtract) locally – much as the sitar player does. If this electron collides inelastically with another particle, the energy released in the process contains also contribution from the stored energy of the magnetic field. Magnetostatic energy is drawn down – without any direct participation of the source of the field inside the planet in this process.

Planetary magnetic field lines

This phenomenon may occur in other magnetized plasmas, and not just cosmic plasmas.

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Consider first a stringed musical instrument with a string under tension (and therefore storing some energy), firmly anchored at two ends. When you strike or pluck the string, it makes musical notes – and thus sound energy. Where did this energy come from? It came entirely from the act of plucking or striking – the energy stored in the string does not contribute to the sound energy. The stored energy is not *available* at the location of plucking and striking.

So it is with magnetic field. Consider a planetary magnetic field line (liken this to the string) at a location O in the magnetosphere. The source of this magnetic field is within the planet (and can be likened to the anchors in the above analogy). If at the location O you bring a small compass needle, it will align itself to the planetary magnetic field line. The energy needed to effect this alignment comes from the energy you expend in bringing the compass there. The energy of the planetary magnetic field at O is not *available* there to be tapped, or, "drawn down".

Let's make this example a little more realistic. Suppose that you apply an electric field E at O, and this electric field accelerates an electron, which curves around the magnetic field. The electron thus gains some extra kinetic energy. It the electron now collides with another particle and gives up its entire energy to produce heat, where did this energy come from? It came from whatever the kinetic energy the electron initially possessed plus the work done on the electron by the electric field. Again, the energy in the planetary magnetic field is not available to take part in this local process at O, far away from the source.

This analogy – to the extent that it applies – is consistent with the current view of the nature of magnetic field. This view is the solid granite foundation of many developments, including the entire science of plasma physics and the entire enterprise of "hot" fusion energy research. If the drawdown effect existed, it would invalidate the tacit assumption of its nonexistence that underlies many developments. We can summarize the above discussion by the statement:

The magnetic energy drawdown effect is forbidden in the present formulation.

SO WHY BRING IT UP AT ALL?

Because I am questioning the entire current view of the nature of magnetic field. However, if I tell you what this view is, I would be altering the sequence of ideas in the order that I published them. So first I say that there exists a drawdown effect, and then I prove it. Then I use this result to elaborate on the nature of magnetic field.

The way I saw it, the drawdown effect is rather difficult to properly formulate. I therefore took a two-pronged approach: First I showed the effect in a dielectric gas in a magnetic field – using theoretical results I derived earlier. Encouraged by this, I then tried to show the same in a plasma in a magnetic field.

WHAT HAPPENS TO THE STRING ANALOGY IN THE CASE OF DRAWDOWN?

Imagine the string of the musical instrument now as being made up of a large number of fine strands. If, when you pluck or strike the string, one of these strands breaks at the point of striking or plucking, some energy of the string is released at that point. In the case of a plasma, this snapping of the strand corresponds to inelastic collisions.

MY ISSUE IN PLAIN LANGUAGE

Before you go to the papers and the reviews, I will provide a clear orientation. Consider a charged particle in a static magnetic field – initially at rest. An electromagnetic wave propagates such that its electric field is perpendicular to the said magnetic field. Then I posit the following steps which are absolutely correct:

1. The particle moves in a closed loop (oval). Its size and shape are determined by the static magnetic field.

2. This loop has a magnetic moment which is opposed to the static magnetic field.

3. So, the particle has kinetic energy and the loop has inductive energy.

Suppose this particle collides inelastically with another particle and its inductive energy is transformed to kinetic energy.

Now I posit what is new and is subject to review:

4. This inductive energy that is lost (converted to heat) comes partly from the em wave and partly from the static magnetic field. Since the collision cannot perform a budgetary analysis and distinguish between sources of energy, it does not know how to leave behind the amount of energy that came from the static field.

It is true that the static magnetic field will remain unchanged after this process. That is because the battery will replenish the field. The confining magnetic field is inviolate only in this sense: Your wall outlet voltage is always at 120 V regardless of how many devices you are running.

Two papers follow: A published paper on the drawdown effect in dielectric; and a representative manuscript for the same in a plasma.

The results of my many submissions of the idea to many journals can be summarized as follows: The review comments range from *The idea is wrong* to *The idea is well-known as plasma diamagnetism*, including varying degrees of skepticism in between. Also cutting insults.

LETTER TO THE EDITOR

Transformation of magnetostatic energy

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Abstract. Energy in a static magnetic field can be converted to other forms such as mechanical energy and heat. This is done by perturbing the magnetostatic energy by an electromagnetic wave—generating what has been described earlier as a 'companion wave'. When energy is drawn from this latter wave, the magnetic field decays.

The local energy in a static magnetic field in a region far away from the sources of this field is at present thought to be an abstract notion, since there are no known processes by which this energy can be locally altered or transformed. Straightforward consequences of an electromagnetic (EM) theory explored recently [1], however, point to the possibility that this energy may be perturbed in a certain way, and the perturbed energy can in turn be converted to other forms of energy. The present letter demonstrates this phenomenon by referring to a simple dielectric medium and using elementary physics.

A static, uniform magnetic field $\boldsymbol{B}_0$ parallel to the z direction of a Cartesian coordinate system, initially in vacuum, is considered. A plane EM wave propagates in the x direction such that the electric and the magnetic fields of the wave are

$$\boldsymbol{e} = e_0 \sin(\omega t - kx)\boldsymbol{a}_y \tag{1}$$

$$\boldsymbol{b} = b_0 \sin(\omega t - kx)\boldsymbol{a}_z \tag{2}$$

where $\omega = 2\pi f$ (f = the frequency of the wave), $k = 2\pi/\lambda$ (λ = the wavelength), and e_0 and b_0 are the field amplitudes. The region of space under consideration is assumed to be so far away from the sources of the static magnetic field and the EM wave that these sources do not contribute to the energy conservation in local interactions as they occur. The magnetic energy densities in the static magnetic field and the wave magnetic field are $U_0 = B_0^2/2\mu_0$ and $u = b^2/2\mu_0$ (μ_0 = permability of free space), respectively. However, the net magnetic energy density in the medium is

$$U = U_0 + u + \hat{U} \tag{3}$$

with

$$u = u_0 \sin(\omega t - kx) \tag{4}$$

$$\hat{U} = \hat{U}_0 \sin(\omega t - kx) \tag{5}$$

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where $u_0 = b_0^2/2\mu_0$, $\hat{U}_0 = B_0 b_0/\mu_0$, and where $\hat{U} = B_0 b/\mu_0$ is the energy of interaction between the two magnetic fields, representing work done by one field on the other. It has been shown that the interaction energy $\hat{U}$ is just as real and as observable as the EM wave energy u [1]. The spatial and temporal oscillations of $\hat{U}$ constitutes a wave behaviour which has been termed a companion wave (since it accompanies an EM wave).

The fact that the flow of the interaction energy is as real and observable as that of the EM wave energy means that the former can perform work on and transfer energy to physical systems, as does the latter. To demonstrate this, a dielectric gas with a mass density ρ and a linear polarizability χ is chosen as the physical system. What results is a type of magnetohydrodynamic interaction that occurs in a purely dielectric fluid [2–5]. In the oscillatory electric field $\boldsymbol{e}$ the dipolar electric charges in each molecule alternately move towards and away from each other, and these movements of the charges in the magnetic fields $\boldsymbol{b}$ and $\boldsymbol{B}_0$ give rise to microscopic forces on the molecule (for a discussion of this dielectric force, see, e.g., [6]). The net force on a unit volume is the cross-product of the dielectric polarization current density and the magnetic field:

$$\boldsymbol{F} = (\omega\chi^{1/2}/c)u_0 \sin 2(\omega t - kx)\boldsymbol{a}_x + (\omega\chi^{1/2}/c)\hat{U}_0 \cos(\omega t - kx)\boldsymbol{a}_x \tag{6}$$

c being the velocity of light in the medium. The instantaneous velocity $\boldsymbol{v}$ of the gas is found from Newton's law $\mathrm{d}\boldsymbol{v}/\mathrm{d}t = \boldsymbol{F}/\rho$ to be

$$\boldsymbol{v} = -(\chi^{1/2}/2\rho c)u_0 \cos 2(\omega t - kx)\boldsymbol{a}_x + (\chi^{1/2}/\rho c)\hat{U}_0 \sin(\omega t - kx)\boldsymbol{a}_x \tag{7}$$

so that the instantaneous kinetic energy is

$$\varepsilon = (\chi/8\rho c^2)u_0^2 \cos^2 2(\omega t - kx) + (\chi/2\rho c^2)\hat{U}_0^2 \sin^2(\omega t - kx) - (\chi/2\rho c^2)u_0\hat{U}_0 \cos 2(\omega t - kx)\sin(\omega t - kx) \tag{8}$$

and the time-average kinetic energy is

$$\langle\varepsilon\rangle = (\chi/16\rho c^2)u_0^2 + (\chi/4\rho c^2)\hat{U}_0^2. \tag{9}$$

The first term on the right-hand side represents an energizing of the dielectric by the EM wave, and is independent of the field B_0. The second term represents mechanical energy derived from the interaction energy. This, however, is not a primary energy source in the medium but is composed of the EM wave energy and the magnetostatic energy. Since the second term can be arbitrarily high for an arbitrarily high value of B_0 and may exceed the energy density of the EM wave, it follows that part of this mechanical energy must come from the energy in the field B_0. The second term is written separately as

$$\langle\varepsilon\rangle_i = Cu_0U_0 \tag{10}$$

with $C = \chi/\rho c^2$. This shows the relative contributions of u and U_0 to $\langle\varepsilon\rangle_i$. If U_0 is held constant and u_0 increases by Δu_0, then the portion of Δu_0 that goes to increase $\langle\varepsilon\rangle_i$ by $\Delta\langle\varepsilon\rangle_i$ is

$$\Delta\langle\varepsilon\rangle_i = CU_0\Delta u_0.$$

Similarly, if u_0 remained unchanged and U_0 were higher by ΔU_0, the portion of ΔU_0 going to $\langle\varepsilon\rangle_i$ is

$$\Delta\langle\varepsilon\rangle_i = Cu_0\Delta U_0$$

If a part of the energy $\langle\varepsilon\rangle$ were to continually dissipate as heat, so would a part of $\langle\varepsilon\rangle_i$, and thus the energies u_0 and U_0 would both decrease. The result is an attenuation of the EM wave and a decay of the static magnetic field. This local loss of energy in the static magnetic field will eventually be communicated to the sources of B_0, which will act to complete the overall energy budget.

To complete the demonstration, it is noted from equations (9) and (10) that a loss of energy $\mathrm{d}\langle\varepsilon\rangle$ by dissipation may be written as

$$\mathrm{d}\langle\varepsilon\rangle = C_1 u_0\,\mathrm{d}u_0 + CU_0\,\mathrm{d}u_0 + Cu_0\,\mathrm{d}U_0 \tag{11}$$

where $C_1 = C/8$. If the magnetic field B_0 *does not decay* (i.e., if $\mathrm{d}U_0 = 0$), then

$$\mathrm{d}u_0 = \mathrm{d}\langle\varepsilon\rangle/(C_1 u_0 + CU_0).$$

According to this, the higher the field B_0, the less the energy the wave has to provide to account for the same dissipation. Thus the dissipation may even exceed the available energy in the wave. Since this is not possible, it follows that some energy must be drawn from U_0, so that B_0 must decay.

The above discussion may now be rationalized by considering the actual mechanism by which a portion of U_0 couples into the motion of a molecule. The polarization charges in the molecule moving in the field B_0 execute a microscopic current loop which continually exchanges energy with this field. When the kinetic energy of the molecule dissipates as heat, so does a portion of the magnetic energy U_0. An example of a dielectric medium where this effect may be appreciable is the 'Rydberg gas' mode of excited atoms or molecules that achieve large polarizability just prior to ionization or dissociation [7, 8].

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MAGNETOSTATIC ENERGY DRAWDOWN IN A COSMIC PLASMA

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Figures: 2

ABSTRACT

A charged particle in a cosmic plasma is often subjected to a static magnetic field and electromagnetic wave fields. These fields together produce a curved trajectory, and the particle feels a force due to this curvature. Analysis of the orbit shows that the particle takes energy from the magnetic field in the form of kinetic energy, and converts this energy to heat on collision with other particles. The result is a drawdown of the magnetostatic energy. Some cosmic environments where this effect may be relevant are suggested, and one of these (sunspot) is discussed in detail.

I. INTRODUCTION

An externally imposed static magnetic field in a steady state, linear plasma is considered inviolate with regard to local processes in the plasma. The attenuation of an electromagnetic (EM) wave in the plasma, for example, does not affect the magnetostatic energy. But this result overlooks certain electrodynamic processes which, when included, indicate a progressive drawdown of the said energy. Since the magnetic fields in most man-made plasmas are held constant by electromagnets, the effect here is inconsequential. In cosmic plasmas, however, the effect is relevant. The drawdown effect was first suggested in dielectric fluids (De, 1994) which share many properties of plasmas (De, 1988). Wave-magnetic field energy interchange in free space has also been explored (De, 1993).

II. CURVATURE OF A CHARGED PARTICLE TRAJECTORY

A charged particle (mass m, charge q) having a velocity $\mathbf{v}$ ($v \ll c$, the speed of light) in a static magnetic field $\mathbf{B}_o = B_o \mathbf{a}_z$, and the electric field $\mathbf{E} = E_o \sin \omega t \, \mathbf{a}_x$ of an EM wave of frequency f is considered ($\omega = 2\pi f$; $B_o \gg b$, the wave magnetic field). The rest frame of the problem is fixed to the source of $\mathbf{B}_o$. This geometry obtains in many cosmic environments. Initially, the thermal velocity of the particle is neglected. It then moves under the force

$$\mathbf{F} = q [\mathbf{E} + \mathbf{v} \times \mathbf{B}_o] \qquad (1)$$

along a loop or a series of loops ("Orbit 0") executed in one time-period. The elemental length traversed in time Δt on this path is found to be

$$\Delta \mathbf{S}_o(\mathbf{B_o}) = C_o [\omega_o \cos \omega_o t - \omega(\omega/\omega_o) \cos \omega t]\Delta t \, \mathbf{a}_x - C_o [\omega_o \sin \omega_o t - \omega \sin \omega t]\Delta t \, \mathbf{a}_y \qquad (2)$$

where $\omega_o = qB_o/m$, and $C_o = (E_o/B_o)\omega_o^2/[\omega(\omega^2-\omega_o^2)]$. There arises a corresponding orbital magnetic moment $\boldsymbol{\mu}_0$. The change in the kinetic energy of the particle during Δt is

$$\Delta W_o = \mathbf{F}.\Delta \mathbf{S}_o = q\mathbf{E}.\Delta \mathbf{S}_o \qquad (3)$$

III. SPIN AND THE CURVATURE FORCE

A particle in the above orbit turns about an axis (parallel to the z axis) translating with its center. The average angular frequency of this spin is ω. It arises due to coupling between the particle's intrinsic magnetic moment $\boldsymbol{\mu}_s$ and its orbital magnetic moment $\boldsymbol{\mu}_0$.

The spin in turn modifies the path of the particle. To see this, the charge of the particle is assumed to be uniformly and linearly distributed as a rigid body parallel to the instantaneous direction of motion of the center of the particle. This distribution has already been justified, e.g., in calculating the classical self-force on a radiating electron (Cf. Sommerfeld, 1964). The linear extent of the distribution is s_o ($\sim 6.10^{-15}$ m for electrons). The curvature of the trajectory causes a velocity differential along the rigid body in the rest frame [Figure 1(a)]. This velocity is $\mathbf{V}(\mathbf{s}')$, and $\mathbf{v} = \mathbf{V}(0)$. The rest frame magnetic field $\mathbf{b}_{curv}$ at $\mathbf{s}'$ is (*op. cit.*):

$$\mathbf{b}_{curv}(\mathbf{s}') = (\mu_o q/4\pi s_o)\int [\mathbf{V}(\mathbf{s}) \times \mathbf{d}/d^3 + \mathbf{d} \times \dot{\mathbf{V}}(\mathbf{s})/cd^2 - \{\mathbf{d} \times \mathbf{V}(\mathbf{s})\}\{\mathbf{d}.\dot{\mathbf{V}}(\mathbf{s})\}/c^2d^3] ds \quad (4)$$

where $\mathbf{d} = \mathbf{s} - \mathbf{s}'$ (μ_o = free space permeability). For $\omega \ll c/s_o$ the acceleration terms above, and the induced electric field $\mathbf{e}_{curv}$ ($\nabla \times \mathbf{e}_{curv} \sim -\dot{\mathbf{b}}_{curv}$) may be ignored. Being coupled to $\mathbf{B}_o$, the particle can exert a self-force to move itself. This force per unit length on the element ds' is [Figure 1(b)]

$$\mathbf{f}_{curv}(\mathbf{s}') = (q/s_o)\, \mathbf{V}(\mathbf{s}') \times \mathbf{b}_{curv}(\mathbf{s}'), \quad (5)$$

and can also be understood thus: Since $\mathbf{b}_{curv}$ opposes $\mathbf{B}_o$, there is a reduction of the net magnetic force at ds' by the amount f_{curv}. When viewed from the rest frame there is a longitudinal stress, and a net force $\mathbf{F}_c$ on the particle along the unit normal $\mathbf{a}_S$ to the trajectory:

$$\mathbf{F}_c = \int \mathbf{f}_{curv}(\mathbf{s}') \sin \angle(\mathbf{s}', \mathbf{f}_{curv})\, ds' = q\, \mathbf{v} \times \mathbf{b}_c \quad (6)$$

This defines $\mathbf{b}_c$ as the effective curvature field, opposing $\mathbf{B}_o$. The field actually seen by the particle is $\mathbf{B} = \mathbf{B}_o + \mathbf{b}_c$. Equation (1) becomes

$$\mathbf{F} = q\,[\,\mathbf{E} + \mathbf{v} \times \mathbf{B}] \quad (7)$$

IV. THE MODIFIED ORBIT

The orbit of Equation (7) can be developed as a perturbation on Orbit I [$\Delta \mathbf{S}_I = \Delta \mathbf{S}_o(\mathbf{B})$]. The magnetic force $\mathbf{F}_m = q\mathbf{v} \times \mathbf{B}$ is directed along $\mathbf{a}_S$. The

balance of forces along $\mathbf{a}_S$ at any point O at time t is considered [(Figure 2(a)]. Orbit I requires that $\mathbf{F}_m.\Delta\mathbf{S}_I = 0$. Hence, over the next time interval Δt, the particle would proceed normal to $\mathbf{F}_m$. The centrifugal force $\mathbf{F}_R = (mv^2/R)\mathbf{a}_S$ must balance the component of $\mathbf{F}$ along $\mathbf{a}_S$ so that

$$\mathbf{F}_\perp = q(mv^2/qR - vB + E \sin\theta)\, \mathbf{a}_S \qquad (8)$$

must be a null vector, where R is the radius of curvature of Orbit I at O. This defines a function $b_c(v)$. But a function $b_c(v)$ has already been specified by Equations (4)-(6). Therefore the new function is inadmissible, and the actual path $\Delta\mathbf{S}_{II}$ (Orbit II) differs from $\Delta\mathbf{S}_I$. The particle feels a force $\mathbf{F}_\perp \neq 0$ and executes a constrained motion along $\Delta\mathbf{S}_{II}$ [Figure 2(b)]:

$$\Delta\mathbf{S}_{II} = \Delta\mathbf{S}_I + (\Delta t^2/2m)\, \mathbf{F}_\perp. \qquad (9)$$

V. TRANSFORMATION OF MAGNETOSTATIC ENERGY

The change in kinetic energy now is

$$\Delta W_{II} = \mathbf{F}.\Delta\mathbf{S}_{II} = q\mathbf{E}.\Delta\mathbf{S}_{II} + q[\mathbf{v}\mathbf{x}\mathbf{B}_o].\Delta\mathbf{S}_{II} + q[\mathbf{v}\mathbf{x}\mathbf{b}_c].\Delta\mathbf{S}_{II} \qquad (10)$$

There are only two sources of energy in the medium: the EM wave, and the energy field $U_o = B_o^2/2\mu_o$. The first term on the right hand side above represents work done by the wave. The third term represents a reduction in this work, since $\mathbf{b}_c$ derives from the spin which in turn derives from the wave. In the second term the force is formed of the velocity and the magnetostatic field. But the particle cannot take energy from itself.

Therefore only the field U_o can be the source of the time-average kinetic energy:

$$\xi = \langle q[\mathbf{v}\mathbf{x}\mathbf{B}_o].\Delta\mathbf{S}_{II}\rangle = (\mu_o^{1/2} q/\sqrt{2}m)\ \langle vF_{\perp}\Delta t^2\rangle U_o^{1/2} \qquad (11)$$

VI. DRAWDOWN

When the particle collides with another particle in a plasma ξ is converted to heat, raising the temperature of the plasma. Since after collision the subject particle has no memory of its direction, ξ is never returned to the field U_o. This local depletion of U_o must eventually be accounted for globally at the source of $\mathbf{B}_o$. When the thermal velocity v_{th} is introduced, the field $\mathbf{b}_c$ still arises in a frame moving with the guiding center of the particle, so that the preceding considerations still apply (even with $v_{th} \gg v$).

Hence the rate of loss of energy per unit volume is $\partial U_o/\partial t = \xi N_q \nu$ W m^{-3}. Here ν is the number of collisions the subject particle (with a number density N_q) has with other particles per second. The following assumptions are implicit: (i) the average volume N^{-3} per particle in the plasma (density N) $\gtrsim$ the orbital volume, ~ C_o^3; (ii) the mean time ν^{-1} between collisions is $\gtrsim$ the period of the wave, 1/f; and (iii) $f \gtrsim f_{pl} = (N_e e^2/\varepsilon_o m)^{1/2}$, the plasma frequency ($N_e$, e = electron number density, charge; ε_o = permittivity of free space).

VII. QUANTITATIVE ESTIMATIONS

Computation of the drawdown effect involves a multitude of considerations. Here order-of-magnitude estimates are made for only a part of the effect, and for electrons which are more important than ions. An approximate analytical value for b_c in Equation (6) can be found when Orbit 0 is *nearly* circular, having a radius $R_o \gg s_o$. The circularity approximation is valid near $\omega \sim \omega_o$. The resonance at $\omega = \omega_o$ is avoided. Now the value b_{co} of b_c is found to be

$$b_{co} \sim \mu_o e v \Lambda / 4\pi s_o R_o \sim \mu_o e \Lambda / 4\pi s_o,$$

where $v = R_o\omega$, and Λ is a factor of the order of unity arising from avoidance of singularities. The orbital magnetic moment of the electron is $\boldsymbol{\mu}_0 = - (e\omega R_o^2/2)\mathbf{a}_z$. Since $F_\perp$ is a continuous function near $b_c = 0$, and since near circularity of the orbit $v = R_o\omega$ and $\partial\theta/\partial b_c \approx 0$, it follows from Equation (8) that for $b_c \ll B_o$, $F_\perp \sim (\partial F_\perp/\partial b_c) b_{co} \sim e v b_{co}$. Hence an estimate for ξ is

$$\xi_o \sim 2\pi^2 e^2 v\, {}^2 B_o b_{co}/m\omega^2$$

Setting $\omega \approx \omega_o$ and using $v = \pi e E_o/\sqrt{2}m\omega$ and the flux density $S = E_o^2/2\mu_o c$ of the wave, one has:

$$b_{co} \sim 0.5\, B_o$$
$$\xi_o \sim 3.10^{-26}\, B_o^{-2}\, S$$

Since the assumption $b_{co} \ll B_o$ turns out to be weak, the result is approximate on this ground as well. It shows reasonably however that a strong EM flux favors drawdown. This suggests some likely places where the effect may be relevant: the solar atmosphere ($B_o \sim 10^{-2}$-1 T; $f_o = \omega_o/2\pi$ in radiofrequency range) and possibly interior; magnetospheres of pulsars and neutron stars ($B_o \sim 10^8$ T; f_o in X-ray and gamma ray range); and the Earth's plasmasphere ($B_o \sim 10^{-5}$ T; f_o in radiofrequency range) illuminated by the quiet or active sun.

VIII. APPLICATION EXAMPLE: SUNSPOTS

In the sunspot umbra the magnetic field $\mathbf{B_o}$ is largely along the solar vertical, and the solar EM waves propagate also vertically. Hence the geometry of Section II holds for any polarization state of the waves. The physical conditions here may be described from observation and modeling (see e.g. Allen, 1983; Zirin, 1988; Semel *et al*, 1991; Skumanich, 1992). A density of neutrals $N_n \sim 10^{24}$ m^{-3}, and a temperature $T \sim 4.10^3$ K are assumed. With an ionization ratio of 10^{-6}, $N_e \sim 10^{18}$ m^{-3}. Then electron-neutral collisions dominate. For a typical $B_o \sim 0.4$T (4000 G), $f_o \sim 11$ GHz. The spectral flux density S_ω ($S = S_\omega \Delta f$, Δf being the bandwidth) of radio waves at the level of the photosphere can be estimated from its measured values at the Earth. The value of S_ω for the continuum emission at ~ 11 GHz here is about $\sim 10^{-19}$ W m^{-2} Hz^{-1} (Jursa, 1985; Nelson et al, 1985). The corresponding photospheric value is $\sim 5.10^{-15}$ W m^{-2} Hz^{-1}. Since the radio emission is broadband, one may use a bandwidth $\Delta f \sim 100$ MHz (< 1 per cent of f_o) and still use the relation $S = E_o^2/2\mu_o c$. For a weakly ionized plasma $\nu \sim 2.10^{-15} N_n T^{1/2}$ s^{-1} (Cf. Krall and Trivelpiece, 1973). Then one

finds $\partial U_o/\partial t \sim -10^{-2}$ W m^{-3}. Generalizing the "local" results to global ones, one has the estimates

$$\partial B_o/\partial t \sim \mu_o(\partial U_o/\partial t)/B_o \sim -30 \text{ Gauss/day}$$

$$\partial T/\partial t \sim -2(\partial U_o/\partial t)/3kN_n \sim 40 \text{ K/day},$$

where k is the Boltzmann constant. These numbers indicate an evolution towards photospheric conditions over the life-time of a sunspot (many days).

IX. CONCLUDING REMARKS

An experimental verification of the drawdown effect may in principle be attempted in a discharge tube plasma in a waveguide. The field $\mathbf{B}_o$ is imposed by a permanent magnet. The parameters are so chosen as to predict a measurable weakening of the magnet over the duration of the experiment.

In sum, a phenomenon of potential interest in cosmic electrodynamics has been deduced and an example of its applicability demonstrated. In view of an earlier discussion (De, 1996), the drawdown process may represent rather a passage of mass to energy than a transformation of energy. Thus the present discussion may be of interest in the larger context of cosmology.

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FIGURE CAPTIONS

FIGURE 1. Illustration of the curvature fields and forces: (a) A charged particle moving in a curved trajectory is assigned a finite size, corresponding to a one-dimensional charge distribution tangential to the trajectory. The arrows indicate the velocities $\mathbf{V}(\mathbf{s})$ of different segments of this distribution. (b) The curvature forces $\mathbf{f}_{curv}$ on the different points $\mathbf{s}'$ of the charge distribution.

FIGURE 2. Illustration of the modified orbit: (a) Configuration of forces acting on the particle at any point O of the orbit. The centrifugal force is not shown. Path II is the actual direction of continuation of the orbit past O. Path I is the hypothetical direction of continuation. (b) The displacements $\Delta\mathbf{S}_I$ and $\Delta\mathbf{S}_{II}$.

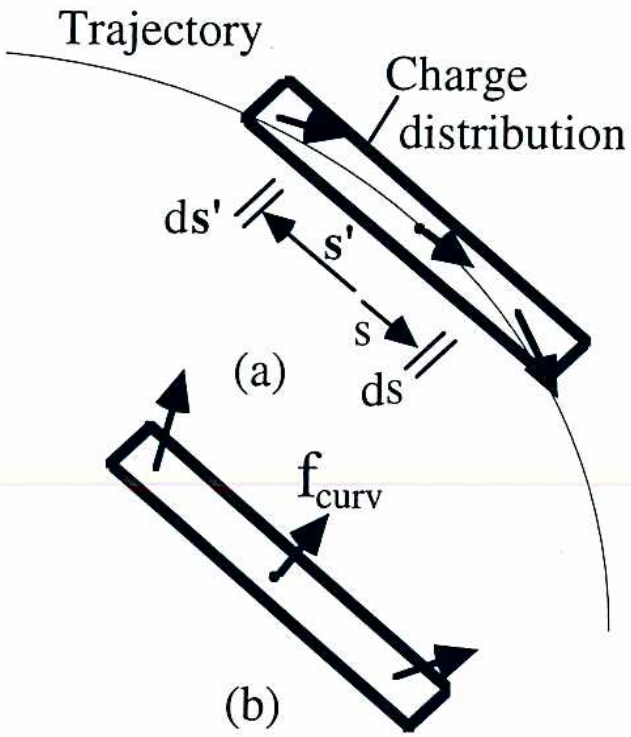

FIGURE 1

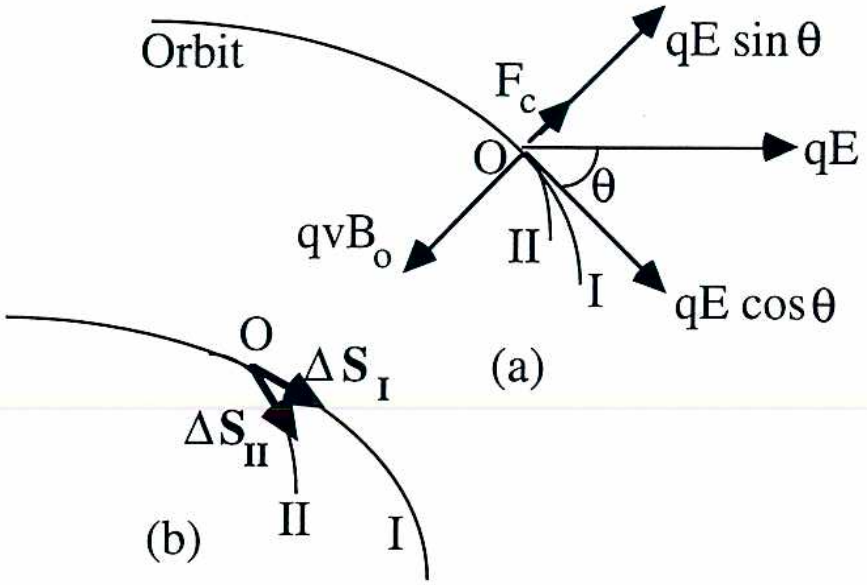
Orbit
F_c
$qE \sin\theta$
O
qE
θ
qvB_o
II
I
$qE \cos\theta$
O
ΔS_I
(a)
ΔS_{II}
II
(b)
I

FIGURE 2